HEAT SWEEP ANALYSIS OF REINJECTION RECHARGE AT THE LOS AZUFRES GEOTHERMAL FIELD

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ABSTRACT

The SGP 1-D Heat Sweep Model was used to evaluate the thermal effects of reinjection recharge of separated brine and turbine condensate from several candidate injection wells at the three major production zones of the Los Azufres geothermal field in Michoacan, Mexico. Data for a series of simulations for ten potential reinjection-production well pairs were compiled from discussions with the senior staff at Los Azufres on available reservoir characteristics and expected long-term production conditions. The simulations provide an estimate of the cooldown of the wellbore fluid temperature as a function of production time. The results are an estimate of the time to the production abandonment temperature corresponding to the minimum inlet pressure to the generating unit turbines. Analyses were made for linear, radial, and doublet recharge flow geometries to simulate rapid to long-term recharge breakthrough. The results show a distribution of potential breakthrough times, comprising a risk of early thermal breakthrough times to the nearest production well for some of the designated reinjection wells and a potential benefit for significant enhanced thermal energy recovery for other reinjection wells.

INTRODUCTION

Reinjection of separator brines and turbine condensate is an integral part of the reservoir management plan for Los Azufres geothermal field in Michoacan, Mexico. In the development of the three major production zones of the field for both small portable wellhead and large central units, brines will be disposed by injection into non-productive stepout wells at the margins of the production zones. The selection of specific wells requires adequate assurance that the risk of premature thermal cooldown at the production wells by the reinjected fluid is small. However, reinjection of the cooled brine at an appropriate distance from the production wells not only solves the waste brine problem, but also provides reservoir management benefits of maintaining reservoir pressure in the production zone and the potential for secondary thermal energy recovery from the reservoir interval between injection and production wells. Ramey, Kruger, and Raghavan (1973) noted that most of the heat contained in a hydrothermal resource resides in the formation rock rather than in the geothermal fluid. This stored heat can be extracted by two processes: (1) flashing the contained liquid to steam within the pore space (until the liquid content is exhausted) or (2) recycling colder fluid back into the formation (at a rate consistent with the rate of heat extraction from the rock matrix).

The SGP 1-D Heat Sweep Model was developed for use as a simple heat transfer model for early prediction of the potential of production fluid cooldown as a result of cold water reinjection into a fractured hydrothermal reservoir. The model is based on the equations for heat transfer from large, irregular-shaped rock blocks in contact with colder recharge fluid flowing in the fracture porosity of the reservoir interval between reinjection wells and production wells. A description of the 1-D linear flow model is given by Hunsbedt, Lam, and Kruger (1984). The model evaluates the mean temperature difference between a collection of fractured rock blocks described by Kuo et al (1977) and Iregui et al (1979) as lumped equivalent-radius spheres and the circulating recharge fluid. The main parameter in the model is the number of heat transfer units, which expresses the ratio of the mean fluid residence time to the thermal time constant for the rock distribution. A large number of heat transfer units implies a reservoir that is heat limited, with the recharge fluid remaining sufficiently long for effective removal of the thermal content of the formation above the recharge fluid temperature. A small number of heat transfer units implies a reservoir that is fluid limited, the residence time being too small for effective heat transfer.

The 1-D linear heat sweep model was improved by Lam (1986) to allow for several types of recharge flow geometry and for mixing of the recharge fluid with reservoir fluid cooling exponentially at a given cooldown rate near the production wells. A further improvement was the addition of a doublet flow sweep model, in which the intrinsic 2-D nature of doublet flow was expressed as 1-D for heat extraction. The flow travel time between wells in a uniform flow field was described by Grove, Beetem, and Sower (1970). The 1-D doublet heat sweep model calculates the heat extraction as the sum of linear hear sweeps in an expanding series of streamline flow crescents connecting the injection and production well pair. A description of the doublet flow heat sweep model is given by Lam and Kruger (1987).

The present joint study builds on the history of cooperative efforts between the Comision Federal de Electricidad (CFE) and the Stanford Geothermal Program (SGP) on the use of the 1-D Heat Sweep Model to evaluate the potential for thermal cooldown at selected production wells in Mexican geothermal fields based on available preproduction reservoir data and planned reinjection practices compiled by field development personnel. The objectives of this joint study were to assist in selection of available non-production wells as candidate reinjection wells, to evaluate the potential for secondary thermal energy recovery for the selected injection wells, and to estimate the time to thermal breakthrough of the reinjection recharge to the production fluid temperature corresponding to the minimum inlet pressure to the turbines.

APPLICATION TO LOS AZUFRES

The development of the three major zones of the Los Azufres geothermal field requires early decision on the choice of reinjection wells for reinjection testing and construction of the surface piping of the return lines. A plan of the proposed collection lines for the three zones, Tejamaniles vapor-dominated zone in the south, El Chino two-phase zone in the center, and Maritaro liquid-dominated zone in the north, is shown in Fig 1. Several of the candidate wells are already being used, some for current operations, such as Az-7 and Az-8 in the Tejamaniles zone, Az-3 in the El Chino zone, and Az-15 in the Maritaro zone. Others are being considered for the new installations, 5-MW wellhead units in the Maritaro zone and the 55-MW central power station in the Tejamaniles zone. Table 1 lists the pairs of injection - production wells selected for this phase of the SGP-CFE joint study.

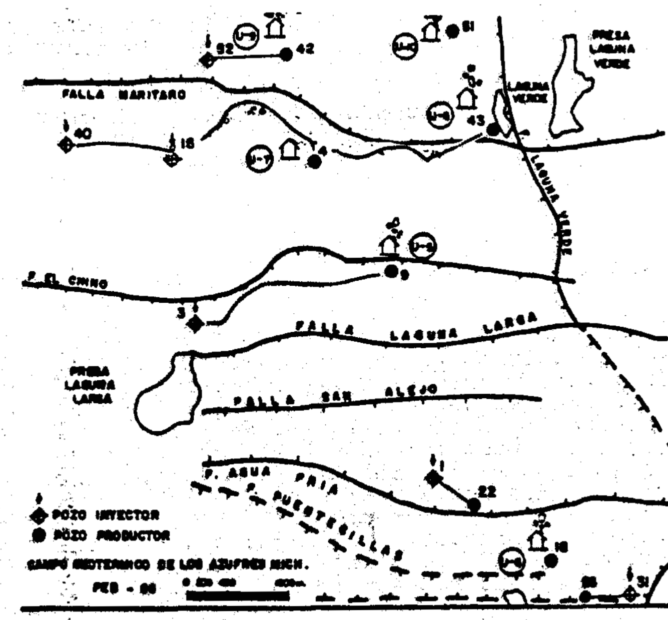

Fig. 1. Planned brine reinjection lines for the three Los Azufres production zones.

In the Tejamaniles zone, in addition to the three 5-MW wellhead units operating since 1982, the newly installed 55-MW central station is expected to come into operation in 1989. Surface piping is being installed for the wells shown in Fig. 1. Two other non-production wells are being held in reserve for testing and possibly reinjection usage, wells Az-1 in the north and Az-31 in the east. These wells are close to two production wells, Az-22 and Az-26, respectively. In the El Chino zone, one 5-MW wellhead unit is operating at well Az-9 with well Az-3 as the injection well. This pair, with its well-defined parallel faults to the north and south provided the basis for an extensive analysis with the linear, radial, and doublet flow sweep models. The initial results of the study on this well pair as part of the development of the 1-D doublet heat sweep model were given by Lam and Kruger (1987). The Maritaro zone is expected to receive four additional 5-MW wellhead portable units during 1988 and 1989. Table 1 shows the planned production wells and the proposed corresponding reinjection wells for these new units. A major problem in the development of the surface facilities is the choice of either Az-15 or Az-40 to provide the bulk of the reinjection capacity for the new units as well as the two units at Az-5 and Az-13 in operation since 1982. The possibility of extending the reinjection area to the north is examined in the well pair Az-52 and Az-42.

Table 1
Los Azufres Heat Sweep Analysis Well-Pair Data*

Proj No.	Unit No.	Inj Well	Prod Well	T(i) (C)	T(r) (C)	Q(i) (t/h)	Q(r) (t/h)	L (m)	H (m)
Tej-1	C	31	26	281	42	208	52	460	135
Tej-2	C	1	22	280	115	95	84	520	491
ECh-3	5	3	9	280	70	44	50	2000	240
Mar-4	7	15	4	279	144	148	66	1410	385
Mar-5	7	40	4	269	22	148	66	2415	721
Mar-6	8	15	51	263	144	n/a	n/a	3200	433
Mar-7	8	40	51	253	22	n/a	n/a	4080	768
Mar-8	9	52	42	264	80	243	122	830	321
Mar-9	10	15	43	253	144	20	65	3240	482
Mar-10	10	40	43	243	22	20	65	4240	818

*Constants for the Study:

T(a)(8 bar)	170 C	Material	andesite
Porosity	10 %	Density	2430 kg/m3
MFS	50 m	Heat Capac	1164 J/kgC
CDR	-0.005/yr	Conductivity	1.72 W/mC

Table 1 also provides the currently available production and reservoir description data compiled by the operating staff at Los Azufres. The thermal conductivity value of 1.72 W/mC was taken from the experimental measurements on Los Azufres cores reported by Iglesias, Contreras, and Garcia (1987). The production data are generally based on short-term flow testing and may change when sustained production is initiated. The flow rates given for the Maritaro wells were estimated from pressure-discharge test data extrapolated to 8-bar wellhead pressure and the results of the simulations should therefore be considered preliminary, subject to change as new operating data become available. However the results of the simulations should be of use in the early decision-making processes for field development.

THE SIMULATIONS

The heat sweep simulations were run to obtain a series of cooldown curves for the sweep fluid arriving at the production well and for the mixed fluid at bottomhole, which combines the arriving sweep fluid with reservoir fluid cooling at a selected exponential cooldown rate. For this study, a value of -0.005 /y was selected as most likely, based on other cooldown studies at Cerro Prieto, Mexico and Wairakei, NZ. The results of the series of simulations are described for each production zone in Los Azufres.

Tejamaniles

The two well pairs in the Tejamaniles zone are characterized by short distance between wells, large flowrates, and small steam fraction, the latter implying a large fraction of the produced fluid becoming reinjection recharge. Heat sweep simulations were run for small angle flow (direct return flow through connecting fractures) and doublet flow (uniform flow over the reservoir zone).

The results of the simulations, given as time to cooldown to an abandonment temperature of 170 C, are summarized in Table 2 for both the arriving sweep fluid and the bottom hole mixed fluid. The cooldown curves for the radial flow runs are given in Figure 2. They are similar in that the combination of short distance and large reinjection flowrate provides a comparatively small number of heat transfer units for the selected fracture porosity and spacing. The situation for well Az-26 is more severe in that the liquid production rate is much larger. The result is a rapid cooldown of the mixed production fluid almost independent of the return flow angle. For Az-22, the smaller production rate and smaller fraction of sweep fluid shows a slower mixed fluid cooldown to the abandonment temperature.

Figure 3 shows the cooldown curves for the Az31-Az26 and Az1-Az22 pairs for doublet flow conditions. The results show the effect of the rapid cooldown by the sweep recharge. The upper curve for the Az31-Az26 pair shows the exponential cooldown of all-reservoir fluid without reinjection compared to the middle curve for the mixed fluid with 80 % sweep fluid. The difference in area between the two curves represents the thermal energy above the abandonment temperature lost by premature cooldown due to reinjection of the surface-cooled brines. The results for the Az1-Az22 doublet flow simulation illustrates the opposite effect. The long time for sweep flow shown in the upper curve results in the mixed fluid having a longer cooldown compared to the reservoir fluid cooling at the given constant rate. In this case, the area between the two bottom hole cooldown curves represents additional thermal energy extracted from the resource.

Table 2
Cooldown Simulations : Tejamaniles Zone

	Time (years) to Ta = 170 C			
	Az31 - Az26		Az1 - Az22	
Radial Sweep Angle	Sweep	Mixed	Sweep	Mixed
5	0.05	0.05	4.8	68.5
10	0.10	0.11	9.9	68.5
20	0.24	0.60	19.4	68.5
30	0.86	1.72	28.7	68.5
40	1.73	2.71	37.8	69.1
Doublet Flow				
with reinjection	24	34	732	333
without injection	--	125	--	220

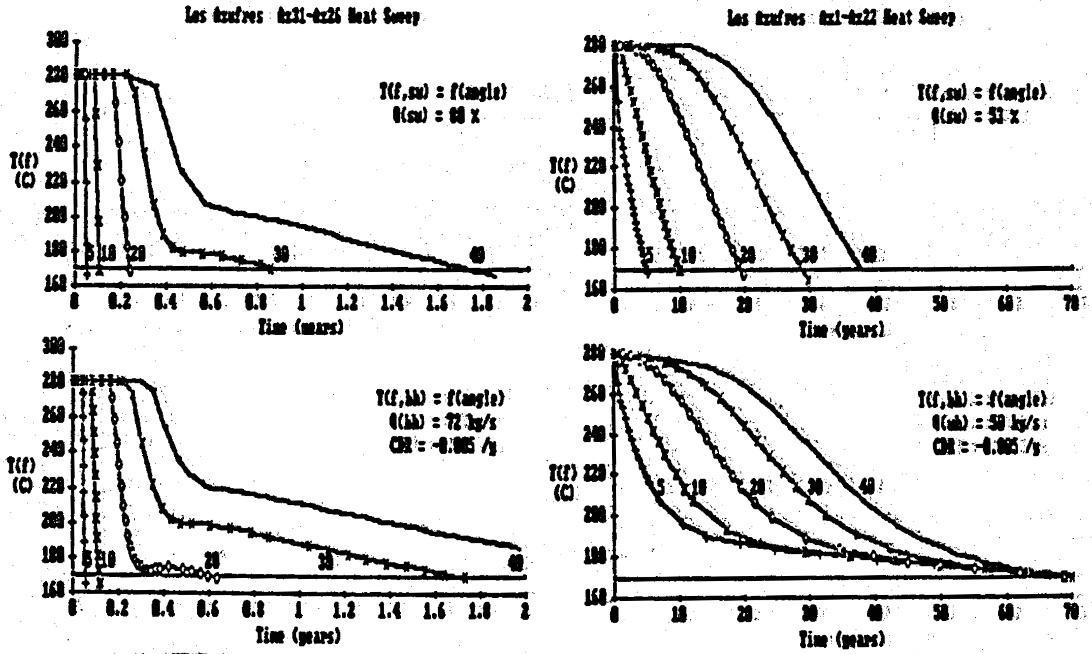

Fig. 2. Cooldown curves for Tejamaniles well pairs as a function of recharge return flow angle. Upper curves are for the sweepfluid at the production well. Lower curves are for the bottom-hole mixed fluid with reservoir fluid cooling at the given cooldown rate.

El Chino

The simulations for the Az-3 injector, Az-9 producer well pair in the El Chino zone were originally run to compare the results for linear, radial, and doublet flow geometries. Two major parallel faults, El Chino and Laguna Grande, about 700 m apart, may act as reservoir boundaries for the El Chino reservoir zone. The simulations were run for linear flow for reservoir widths from 200 to 1200 m, radial flow from 10 to 80 degrees, and doublet flow without boundaries. The results, reported by Lam and Kruger (1987), are given in Table 3. The cooldown curves for the radial flow simulations, similar to those for linear flow, are illustrated in Figure 4. The sweep fluid cooldown curves show an essentially linear increase in cooldown time to abandonment temperature for both reservoir width and radial dispersion angle. The cooldown curves for the mixed bottom hole fluid with the constant exponential cooldown rate of -0.005 /y shows the effect of the increasingly later arrival of sweep fluid at the initial reservoir temperature, which markedly increases the time to the abandonment temperature (170 C) for widths greater than 600 m or for dispersion angles greater than 60 degrees.

Figure 5 shows the results for the doublet flow model. The heat sweep for the small recharge rate of 11.3 kg/s (42% of total production rate) over the large separation distance of 2000 m is essentially negligible in comparison to the assumed reservoir fluid cooldown rate of -0.005 /y. With the continuous arrival of displaced sweep fluid from a very large resource volume at mean initial reservoir temperature, the

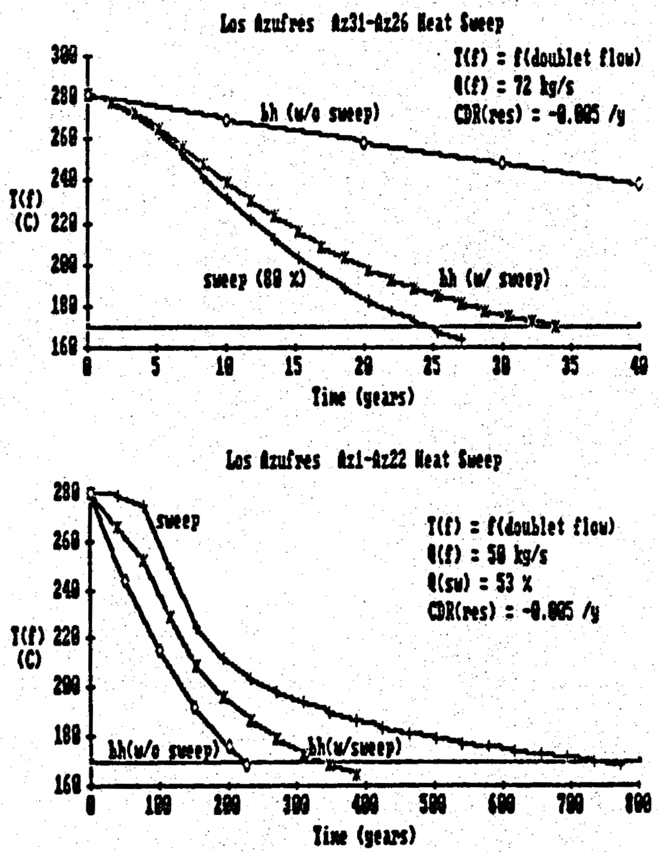

Fig. 3. Cooldown curves for the Tejamaniles pairs for doublet return flow of the reinjected recharge.

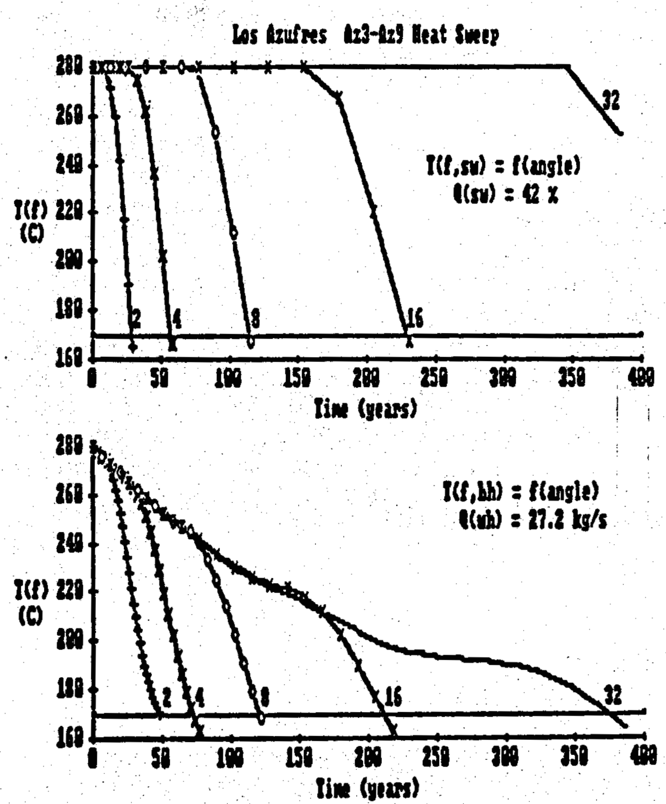

Fig. 4. Cooldown curves for the El Chino well pair as a function of recharge return flow angle.

Table 3
Cooldown Simulations : El Chino Zone*

Time (years) to Ta = 170 C

Linear			Radial			Doublet	
Width (m)	Sweep Flow	Mixed Flow	Angle (o)	Sweep Flow	Mixed Flow	Sweep Flow	Mixed Flow
200	165	160	10	145	144		
400	330	280	20	287	253		
600	490	380	30	430	350		
						5200	450
800	650	500	40	570	450		
1000	820	450	60	860	450		
1200	980	450	80	1150	450		

*from Lam and Kruger (1987)

calculated cooldown is excessively large. Efforts to obtain temperature distribution data away from the reservoir zone are underway. The 1-D model with mean temperature specified for each crescent will result in a more realistic heat sweep simulation. The cooldown from the mixed reservoir fluid is essentially exponential over a 450-year period. However, without the displacement of reservoir fluid by the recharge sweep fluid, the cooldown to abandonment temperature is noted in Figure 5 to be 150 years. The area between the two cooldown curves represents the additional thermal energy extracted by reinjection recharge.

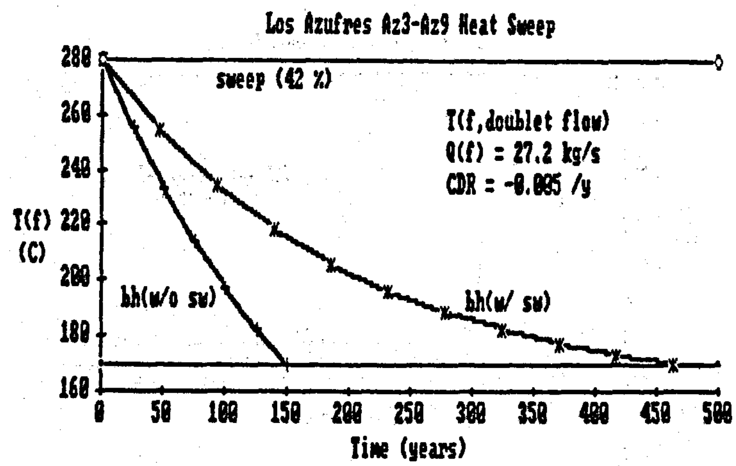

Fig. 5. Cooldown curves for the El Chino well pair for doublet return flow of the reinjected recharge.

Because of the large difference in reinjection temperature assumed for the two injection wells, a separate simulation was run for well pair Az15-Az4 as a function of recharge temperature from Tr = 22 C to Tr = 144 C to examine the effect of selected surface treatment of the brine before reinjection recharge on the production fluid cooldown. The results for this simulation are given in Table 5.

Table 5
Comparison of Cooldown Time with Recharge Temperature Doublet Well Pair Az15-Az4

Recharge Temp (C)	Time to Ta = 170 C: Sweep Fluid (y)	Mixed Fluid (y)
22	717	440
80	1250	600
144	10800	4190

MARITARO

The simulations for the Maritaro zone were carried out in two parts. The first part compares the relative potential for reinjection recharge heat sweep between the two candidate primary reinjection wells, Az-15 (nearer to the production zone) and Az-40 (further to the west). The simulations are for individual well production at wells Az-4, Az-51, and Az-43, and do not take into account the effect of combined flow at the nearest production well, Az-4. This possibility will be evaluated in subsequent joint studies. A summary of the thermal breakthrough times to the abandonment temperature of 170 C for the simulations of reinjection heat sweep from wells Az-15 and Az-40, individually to each of the three production wells is given in Table 4.

The second part of the Maritaro heat sweep simulations was used to evaluate the potential for thermal breakthrough at production well Az-42 with reinjection at well Az-52 located at the northern boundary of the Maritaro zone. The results for the radial and doublet flow cases are given in Table 6.

Figure 6 shows the radial-flow sweep fluid and mixed fluid cooldown for the two candidate reinjection wells Az-15 vs Az-40 at production well Az-4. These results do not take into account reinjection of brine from any other wells (including the presently flowing production wells Az-5 and Az-13) in the Maritaro zone. The data show several interesting features. Well Az-15, being much closer to Az-4 compared to well Az-40, shows a more rapid cooldown to 170 C. With 69 % of the Az-4 production as reinjection recharge, the mixed fluid

Table 4
Cooldown Simulations : Maritaro Zone

Production Well	Flow	Angle	Time (years) to Ta = 170 C, Az-15: Sweep	Az-15: Mixed	Az-40: Sweep	Az-40: Mixed
Az-4	Radial	2	10	94	30	33
		4	18	94	62	64
		8	33	95	126	124
		16	61	93	255	239
		32	117	135	512	464
	Doublet (w/sw)		10900	4190	3620	2120
	(w/o sw)		--	330	--	103
Az-51	Radial	2	51	68	108	107
		4	97	111	220	208
		8	189	197	442	404
		16	373	367	--	--
Az-43	Radial	2	339	320	815	114
	(wo/sw)		--	287	--	80
		4	674	533	1630	114

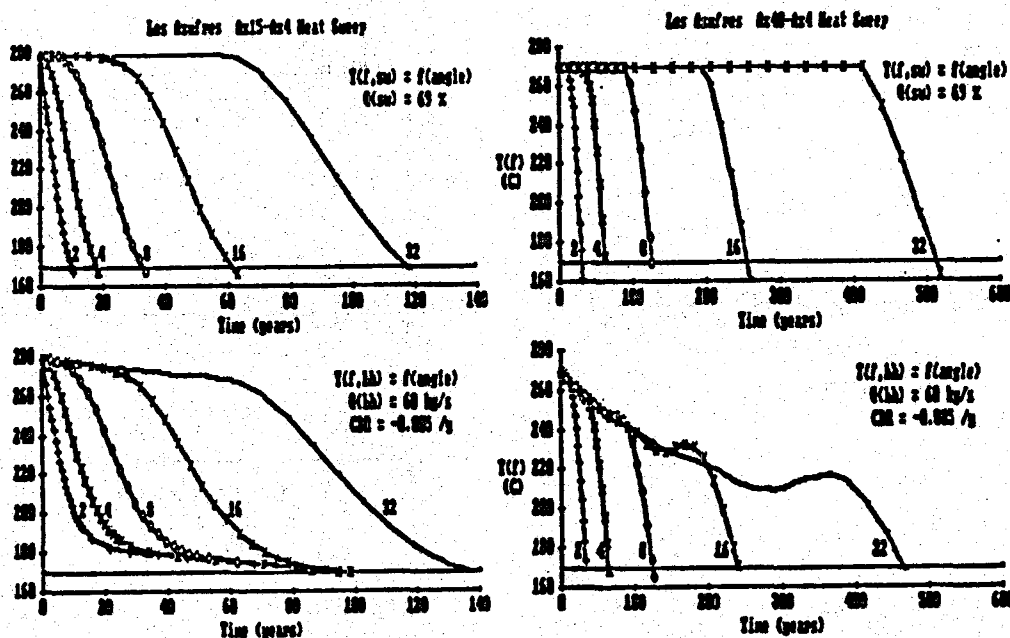

Fig. 6. Cooldown curves for the Az15 and Az40 reinjection wells for Az4 in the Maritaro zone as a function of recharge return flow angle.

Table 6
Cooldown Simulations : Maritaro Zone
Well Pair Az52-Az42

Flow Type	Time to Ta = 170 C: Sweep Fluid (y)	Mixed Fluid (y)
Radial (o)		
5	1.4	4.1
10	4.4	7.7
20	9.9	14.1
40	20.8	25.9
Doublet		
w/ sweep	185	165
w/o sweep	--	143

cooldown is primarily influenced by heat sweep extraction. In contrast, the larger volume of swept rock for well Az-40 provides a greater heat content for extended heat sweep, and for return flow angles greater than about 10 degrees, the later-arriving sweep fluid increases the lifetime above 170 C compared to steady exponential cooldown of the reservoir fluid. Here again, distributed temperature data defining the thermal reservoir would provide more realistic simulations.

A comparison of the cooldown results for the two candidate reinjection wells is given in Figure 7. It is noted that the thermal breakthrough to 170 C for the reservoir fluid without reinjection recharge heat sweep is much faster for the more distant well Az-40 due to the smaller mean initial reservoir temperature and much smaller reinjection recharge fluid temperature, 22 C compared to 144 C contemplated for well Az-15. The mixed fluid cooldown is longer for Az-40 due to the much larger total volume swept through the equal number of flow crescents in the simulation over the assumed constant initial temperature reservoir.

The effect on thermal breakthrough time by differences in reinjection temperature is illustrated in Figure 8. The estimated time of 4190 years for the mixed fluid at the planned reinjection temperature of 144 C (direct reinjection from the brine leg of the separator) would be reduced to 440 years for the reinjection temperature planned for well Az-40 of 22 C (corresponding to long-term surface water storage before reinjection).

Figure 9 shows the heat sweep with reinjection recharge return flow for only an angle of two degrees, corresponding to direct fracture connection between the well pairs separated by more than 3000 and 4000 meters, respectfully. These separation distances implies essentially that wells Az15 and Az40 are not in hydraulic connection with the production wells at the eastern part of the Maritaro reservoir. In this part of the zone, the cooldown rate of the reservoir fluid by intrusion from percolation or groundwater from the near surroundings becomes the dominant cooldown source, especially for the more distant reinjection well Az40.

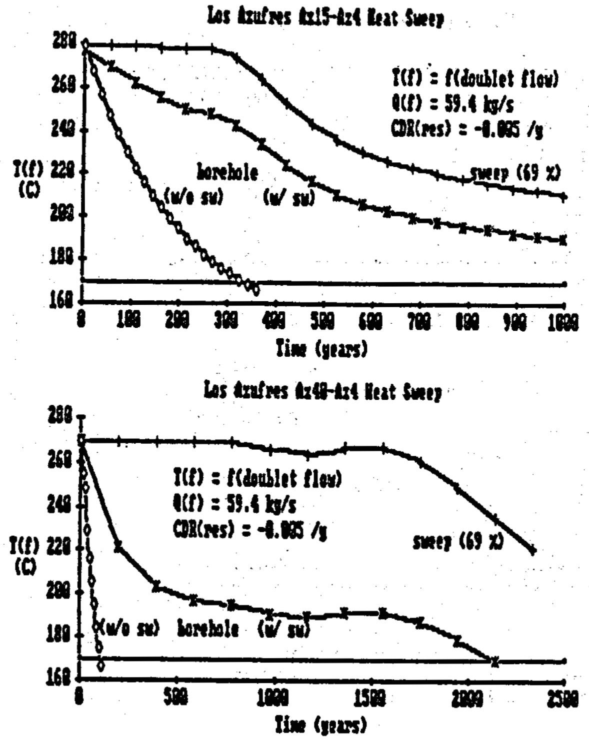

Fig. 7. Comparison of the cooldown curves for doublet flow in the wells of Figure 6.

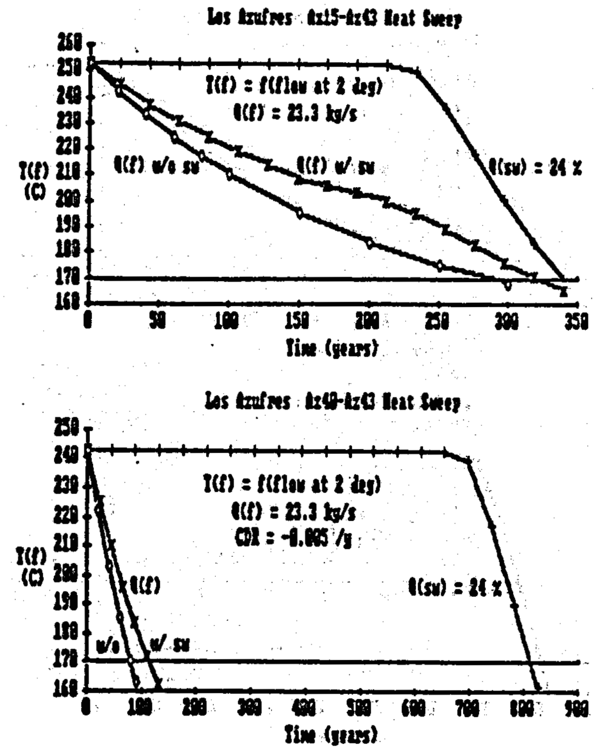

Fig. 9. Comparison of cooldown curves for the Az15 and Az40 reinjection wells at Az43 for direct return flow through an angle of two degrees.

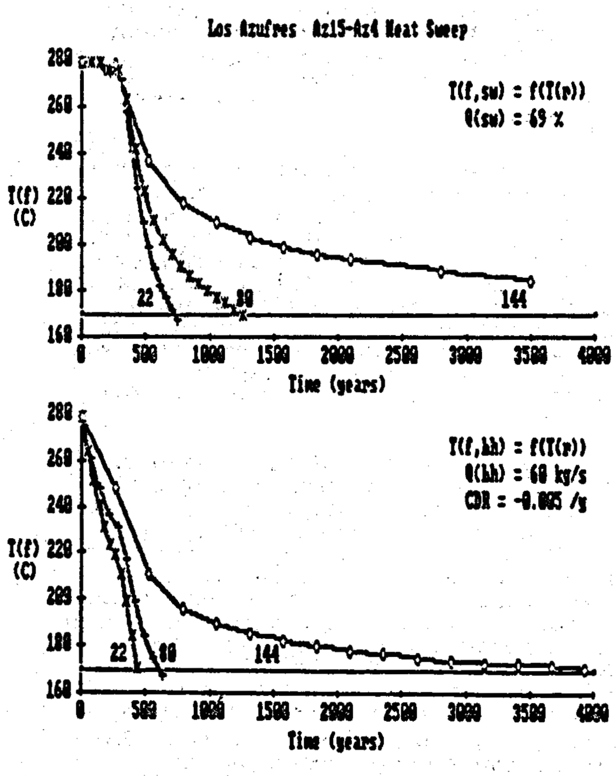

Fig. 8. Cooldown curves for well pair Az15-Az4 as a function of reinjection fluid temperature.

The cooldown simulations for the well pair Az52-Az42, shown in Figure 10, illustrates the same potential heat sweep behavior as noted for well pair Az1-Az22 in the Tejamaniles zone. Although the swept volume is about twice as large, the reinjection rate is also about twice as large, and the breakthrough times are about the same. For doublet flow heat sweep, the longer period of heat extraction shows a somewhat longer breakthrough time compared to no-reinjection production. However, given the large uncertainties in mean reservoir property values, the difference between risk of premature thermal breakthrough and benefit of secondary thermal energy recovery is not readily distinguished.

DISCUSSION

The ten reinjection recharge studies show an interesting variety of observations, from large risk for premature thermal breakthrough in close-by production wells to significantly enhanced thermal recovery at other production wells. The use of non-production wells at the boundary of the Tejamaniles zone for additional reinjection capacity may be useful only for emergency purposes if the nearby production wells are used for continuous steam supply. These wells, further from

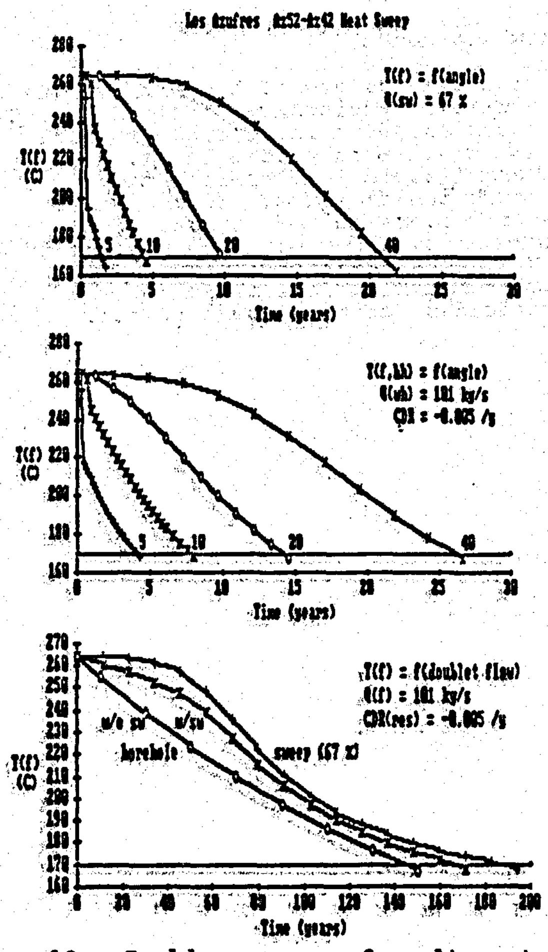

Fig. 10. Cooldown curves for alternate injection well Az52 in northern Maritaro zone as a function of return flow angle and doublet flow.

the center of the all-steam zone, have large liquid fractions and thus provide a disproportionally large volume of separated brine for reinjection compared to the condensate from the all-steam wells.

The El Chino zone appears to be a well bounded thermal zone, and as such could be used for extensive research in the Los Azufres field. The potential for enhanced thermal recovery by reinjection recharge is large, depending on the temperature distribution around the sole production well Az-9. This zone should be of continued interest for increased productivity, and since reinjection has already begun in well Az-3, tracer flow testing at this well pair should provide thermal breakthrough estimates at an earlier time.

The Maritaro zone has two major areas of interest in reservoir management issues, one dealing with the choice of injection wells either central or further out from the production zone, the other dealing with the use of non-producing wells as injection wells at the boundary of the zone when other production wells are nearby. Among the key parameters affecting the potential for early thermal cooldown are the flow path taken by the recharged fluid, the injection temperature, and the natural cooldown rate of mixed recharge and resource fluids near the wellbore. Although a cooldown rate of -0.005 /yr is indicated at other fields, no data are available for Los Azufres to have confidence in the assumed value.

The simulation results given in this report should be used solely as indications for reservoir development planning. The importance of thermal energy extraction from the field is so evident that continued evaluation of reinjection recharge should be carried out by field and modeling efforts. The problem of premature cooldown at production wells close to wells used for reinjection of flow from many production wells needs even greater detailed study. It is recommended that at least one well pair in the Tejamamiles and Maritaro zones be designated for long term investigation of reinjection recharge with physical, tracer, and thermal measurements to increase understanding of the potential of the Los Azufres geothermal field for long-term development and operation.

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